$0^+ \to 2^+$ $0\nu\beta\beta$ decay triggered directly by the Majorana neutrino mass

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Abstract

We treat $0^+ \to 2^+$ $0\nu\beta\beta$ decays taking into account recoil corrections to the nuclear currents. The decay probability can be written as a quadratic form of the effective coupling constants of the right-handed leptonic currents *and* the effective neutrino mass. We calculate the nuclear matrix elements for the $0^+ \to 2^+_1$ $0\nu\beta\beta$ decays of ^{76}Ge and ^{100}Mo, and demonstrate that the *relative* sensitivities of $0^+ \to 2^+$ decays to the neutrino mass and the right-handed currents are comparable to those of $0^+ \to 0^+$ decays.

The neutrinoless double beta ($0\nu\beta\beta$) decay can take place through an exchange of neutrino between two quarks in nulei if the electron neutrino is a Majorana particle and has a nonvanishing mass and/or right-handed couplings [1–3]. There may be other possible mechanisms such as those involving supersymmetric particles which also cause the decay of two neutrons into two protons and two electrons [4–6]. In the present work, however, we restrict ourselves to the conventional two-nucleon and Δ mechanisms of $0\nu\beta\beta$ decay through light Majorana neutrino exchange. From the analises of experimental data on $0^+ \to 0^+$ $0\nu\beta\beta$ decays, stringent limits on the effective neutrino mass and the effective coupling constants of the right-handed leptonic currents have been deduced (see *e.g.* [3,7] and the references quoted therein). On the other hand it still seems to be believed widely that $0^+ \to 2^+$ $0\nu\beta\beta$ decays are sensitive only to the right-handed currents. In view of the theorem that the electron neutrino should have a nonvanishing Majorana mass if $0\nu\beta\beta$ decay occurs anyway [8–10], an observation of $0\nu\beta\beta$ decay due to right-handed interactions would certainly mean also a nonvanishing Majorana mass of the electron neutrino. The purpose of the present work is, however, not to investigate the role of the

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Majorana neutrino mass in such a sense, but to demonstrate that it causes $0^+ \to 2^+$ $0\nu\beta\beta$ decays directly.

A direct contribution of the neutrino mass to $0^+ \to 2^+$ $0\nu\beta\beta$ decays was considered in [3] taking into account the nuclear recoil currents, and the inverse half-life was given as

$$[\tau^{0\nu}_{1/2}(0^+ \to 2^+)]^{-1} = F_{1+}(Z_{1+})^2 + F_{1-}(Z_{1-})^2 + F_{2+}(Z_{2+})^2 + F_{2-}(Z_{2-})^2\,, \tag{1}$$

where $F_{j\pm}$ $(j = 1, 2)$ are the phase space integrals and

$$\begin{aligned} Z_{1\pm} &= M_\lambda\langle\lambda\rangle - M_\eta\langle\eta\rangle \pm M_{\rm m}\frac{\langle m_\nu\rangle}{m_{\rm e}}\,, \\ Z_{2\pm} &= M'_\eta\langle\eta\rangle \pm M_{\rm m}\frac{\langle m_\nu\rangle}{m_{\rm e}}\,, \end{aligned} \tag{2}$$

with the electron mass $m_{\rm e}$ and

$$\begin{aligned} \langle m_\nu\rangle &= {\sum_j}' U^2_{ej} m_j\,, \\ \langle\lambda\rangle &= \lambda{\sum_j}' U_{ej}V_{ej}\,, \\ \langle\eta\rangle &= \eta{\sum_j}' U_{ej}V_{ej}\,. \end{aligned} \tag{3}$$

Here m_j is the mass of the eigenstate Majorana neutrino N_j. U_{ej} and V_{ej} are the amplitudes of N_j in the left- and right-handed electron neutrinos, λ and η the coupling constants of the right-handed leptonic current with the right- and left-handed hadronic currents, and the summations should be taken over light neutrinos ($m_j \ll 100$ MeV). The nuclear matrix elements M_α ($\alpha = \lambda$, η, m) are defined by

$$M_\alpha = \langle 2^+_{\rm F} \| \tfrac{1}{2} \sum_{n,m} \tau^+_n \tau^+_m (\boldsymbol{M}_\alpha)_{nm} \| 0^+_{\rm I}\rangle\,. \tag{4}$$

The explicit forms of the two body operators $\boldsymbol{M}_\lambda$, $\boldsymbol{M}_\eta$ and $\boldsymbol{M}'_\eta$ were given in [11] including the contribution of the Δ mechanism, in which the $0\nu\beta\beta$ decay proceed through an exchange of a Majorana neutrino between two quarks in the same baryon in a nucleus. On the other hand the operator $\boldsymbol{M}_{\rm m}$ was derived in [3] as

$$(\boldsymbol{M}_{\rm m})_{nm} = -\tfrac{1}{2} i m_{\rm e}\Big\{[\boldsymbol{r}_{nm} \otimes (\boldsymbol{\sigma}_n C_m - \boldsymbol{\sigma}_m C_n)]^{(2)}$$

$$+i(g_{\rm V}/g_{\rm A})[\boldsymbol{r}_{nm}\otimes(\boldsymbol{D}_n\times\boldsymbol{\sigma}_m-\boldsymbol{D}_m\times\boldsymbol{\sigma}_n)]^{(2)}$$
$$+(g_{\rm V}/g_{\rm A})^2[\boldsymbol{r}_{nm}\otimes(\boldsymbol{D}_n-\boldsymbol{D}_m)]^{(2)}\Big\}H(r_{nm})\,, \tag{5}$$

where $\boldsymbol{r}_{nm}=\boldsymbol{r}_n-\boldsymbol{r}_m$, $H(r)$ is the neutrino propagation function, $g_{\rm V}$ and $g_{\rm A}$ the vector and axial vector coupling constants. C_n and $\boldsymbol{D}_n$ are the recoil correction terms to the axial vector and vector nuclear currents [2,12] given by

$$\begin{aligned} C_n &= (\boldsymbol{p}_n+\boldsymbol{p}'_n)\cdot\boldsymbol{\sigma}_n/2M\,, \\ \boldsymbol{D}_n &= [\boldsymbol{p}_n+\boldsymbol{p}'_n-i\mu_\beta\boldsymbol{\sigma}_n\times(\boldsymbol{p}_n-\boldsymbol{p}'_n)]/2M\,, \end{aligned} \tag{6}$$

where $\boldsymbol{p}_n$ and $\boldsymbol{p}'_n$ are the initial and final nucleon momenta, M the nucleon mass, and $\mu_\beta=4.7$. The above expression for $\boldsymbol{M}_{\rm m}$ is, however, not suitable for numerical calculations as it stands. Therefore, as was done for $\boldsymbol{M}_\lambda$, $\boldsymbol{M}_\eta$ and $\boldsymbol{M}'_\eta$ in [11], we expand it in terms of the operators $\boldsymbol{M}_{inm}$ with simpler spin and orbital structures,

$$(\boldsymbol{M}_{\rm m})_{nm}=\sum_i C_{{\rm m}i}\boldsymbol{M}_{inm}\,. \tag{7}$$

We define the matrix element M_i of the operator $\boldsymbol{M}_{inm}$ analogously to Eq. (4). The coefficients $C_{{\rm m}i}$ and the two-body operators $\boldsymbol{M}_{inm}$ are listed in Table 1, where

$$\begin{aligned}
&h=r_{nm}H(r_{nm})\,, && h'=-r_{nm}H'(r_{nm})\,,\\
&\boldsymbol{S}_{\lambda nm}=[\boldsymbol{\sigma}_n\otimes\boldsymbol{\sigma}_m]^{(\lambda)}\,, && \boldsymbol{S}_{\pm nm}=\boldsymbol{\sigma}_n\pm\boldsymbol{\sigma}_m\,,\\
&\boldsymbol{y}_{Knm}=[\hat{\boldsymbol{r}}_{nm}\otimes\hat{\boldsymbol{r}}_{nm}]^{(K)}\,, && \boldsymbol{Y}_{Knm}=[\hat{\boldsymbol{r}}_{nm}\otimes\hat{\boldsymbol{r}}_{+nm}]^{(K)}\,(r_{+nm}/r_{nm})\,,\\
&\boldsymbol{y}'_{Knm}=i[\hat{\boldsymbol{r}}_{nm}\otimes\boldsymbol{p}_{nm}]^{(K)}\,, && \boldsymbol{Y}'_{Knm}=i[\hat{\boldsymbol{r}}_{nm}\otimes\boldsymbol{P}_{nm}]^{(K)}\,,\\
&\boldsymbol{r}_{+nm}=\boldsymbol{r}_n+\boldsymbol{r}_m\,, && \hat{\boldsymbol{a}}=\boldsymbol{a}/|\boldsymbol{a}|\,,\\
&\boldsymbol{p}_{nm}=\tfrac{1}{2}(\boldsymbol{p}_n-\boldsymbol{p}_m)\,, && \boldsymbol{P}_{nm}=\boldsymbol{p}_n+\boldsymbol{p}_m\,.
\end{aligned} \tag{8}$$

As was described in detail in [11], $\boldsymbol{M}_\lambda$ and $\boldsymbol{M}_\eta$ can be expanded in terms of $\boldsymbol{M}_{inm}$ with $1\le i\le 5$, $8\le i\le 13$, and $\boldsymbol{M}'_\eta$ in terms of $\boldsymbol{M}_{inm}$with $i=6$, 7 (for the definition of $\boldsymbol{M}_{inm}$ with $6\le i\le 13$, which do not appear in Table 1, see [11]). Of these operators, $\boldsymbol{M}_{inm}$ with $8\le i\le 13$ are related to the $0\nu\beta\beta$ transitions which involve virtual Δ particles in nuclei, and they are induced by the operator $\boldsymbol{M}_{2nm}$ interpreted as acting on two quarks in a nucleon or a Δ particle.

The new operators $\boldsymbol{M}_{inm}$ with $14\le i\le 25$ appear only in the expansion of $\boldsymbol{M}_{\rm m}$. In the derivation of $C_{{\rm m}i}$ listed in Table 1, we have not taken into ac-

count the Δ mechanism yet. Under the same assumption of the non-relativistic constituent quark model about the Δ mechanism as was made in [11], the operators in Table 1 except $\boldsymbol{M}_{inm}$ with $i = 2$, 16, 17 do not contribute when interpreted as acting on two quarks in a nucleon or a Δ particle. Since the relation $\mu_\beta = g_\mathrm{V} = g_\mathrm{A} = 1$ holds for the quark currents, we see $C_{\mathrm{m}i} = 0$ for $i = 2$, 16. The only possible contribution of $\boldsymbol{M}_{17nm}$ to $\boldsymbol{M}_\mathrm{m}$ is estimated to be about $m_\mathrm{e}/2M$ of the Δ mechanism contributions to $\boldsymbol{M}_\lambda$ and $\boldsymbol{M}_\eta$. Therefore we will neglect the Δ mechanism for the calculation of $\boldsymbol{M}_\mathrm{m}$ in the present work.

We calculate the nuclear matrix elements for $0_1^+ \to 2_1^+$ $0\nu\beta\beta$ decay of ^{76}Ge and ^{100}Mo using the method given in [11]. We describe the initial 0_1^+ and final 2_1^+ nuclear states in terms of the Hartree-Fock-Bogoliubov type wave functions which are obtained by variation after particle-number and angular-momentum projection [11–13]. For the case of ^{76}Ge decay, the calculation of the matrix elements M_i with $1 \leq i \leq 13$ has been performed in [11]. In the present work we calculate only the new ones with $14 \leq i \leq 25$ using the nuclear wave functions obtained in [11]. In order to calculate all M_i with $1 \leq i \leq 25$ for the ^{100}Mo decay, the nuclear wave functions of $^{100}\mathrm{Mo}(0_1^+)$ and $^{100}\mathrm{Ru}(2_1^+)$ are constructed in the same manner as in the case of the ^{76}Ge decay. Table 2 shows the calculated matrix elements M_m for the ^{76}Ge and ^{100}Mo decays as a sum of the products $C_{\mathrm{m}i}M_i$. It should be noted that the matrix elements of the operators with rank 0 spin part, *i.e.* M_1, M_4, M_{14} and M_{15} have the dominant contributions to M_m. Table 3 summarizes the calculated matrix elements M_λ, M_η, M'_η and M_m for the ^{76}Ge and ^{100}Mo decays.

The differential rate for $0^+ \to 2^+$ $0\nu\beta\beta$ decay with the energy of one of the emitted electrons ϵ_1 and the angle between the two electrons θ_{12} can be written as

$$\frac{\mathrm{d}^2 W_{0\nu}}{\mathrm{d}\epsilon_1 \mathrm{d}\cos\theta_{12}} = a^{(0)}(\epsilon_1) + a^{(1)}(\epsilon_1)\mathrm{P}_1(\cos\theta_{12}) + a^{(2)}(\epsilon_1)\mathrm{P}_2(\cos\theta_{12})\,. \quad (9)$$

Each of the angular correlation coefficients $a^{(k)}(\epsilon_1)$ $(k = 0, 1, 2)$ can be expressed as a sum of the products of an electron phase space factor and a second order monomial of $Z_{j\pm}$ defined in Eq. (2). The explicit form of $a^{(0)}(\epsilon_1)$, which yields $(\ln 2)/2$ times the right hand side of Eq. (1) upon integration over ϵ_1, can be readily obtained by combining the relevant equations in [3]. Since the expressions for $a^{(1)}(\epsilon_1)$ and $a^{(2)}(\epsilon_1)$ are rather complicated, they will be given elsewhere. Numerical calculations show that $a^{(1)}(\epsilon_1)$ is dominated by a term with the factor $-(Z_{1+})^2 + Z_{2+}Z_{2-}$ times a positive function of ϵ_1, whereas $a^{(2)}(\epsilon_1)$ by a term with the factor $2Z_{1+}Z_{1-} - (Z_{2+})^2 - (Z_{2-})^2$. For later reference we denote these two factors as $z^{(1)}$ and $z^{(2)}$, respectively.

Figure 1 shows the single electron spectra $\mathrm{d}W_{0\nu}/\mathrm{d}\epsilon_1 = 2a^{(0)}$ and the ratios of

the angular correlation coefficients $a^{(1)}/a^{(0)}$ and $a^{(2)}/a^{(0)}$ for the three limiting cases, (a) $\langle\lambda\rangle \neq 0$, (b) $\langle\eta\rangle \neq 0$ and (c) $\langle m_\nu\rangle \neq 0$. Since the coefficients $a^{(k)}(\epsilon_1)$ depend on the parameters $\langle\lambda\rangle$, $\langle\eta\rangle$ and $\langle m_\nu\rangle$ through $Z_{j\pm}$, the results shown in Fig. 1 are independent of nuclear models for the cases (a) and (c). We can also easily understand the signs of $a^{(1)}$ and $a^{(2)}$ from the relations $z^{(1)} = -(M_\lambda\langle\lambda\rangle)^2$ and $z^{(2)} = 2(M_\lambda\langle\lambda\rangle)^2$ for the case (a), and $z^{(1)} = -2(M_{\rm m}\langle m_\nu\rangle/m_{\rm e})^2$ and $z^{(2)} = -4(M_{\rm m}\langle m_\nu\rangle/m_{\rm e})^2$ for the case (c). On the other hand for the case (b), we obtain $z^{(1)} = -(M_\eta\langle\eta\rangle)^2 + (M'_\eta\langle\eta\rangle)^2$ and $z^{(2)} = 2(M_\eta\langle\eta\rangle)^2 - 2(M'_\eta\langle\eta\rangle)^2$, and consequently a cancellation between the contributions of M_η and M'_η occurs when these are of comparable magnitudes. This is just the case for the ^{100}Mo decay, but not for the ^{76}Ge decay where M'_η is much smaller than M_η so that there is no significant difference between the cases (a) and (b) in the angular correlation. It should also be noted in Fig. 1 that the single electron spectra for all the three cases (a), (b) and (c) have approximately the same shape. This is in contrast with the $0^+ \to 0^+$ decays where the spectrum for $\langle\lambda\rangle \neq 0$ is very different from those for $\langle m_\nu\rangle \neq 0$ or $\langle\eta\rangle \neq 0$ [2,3].

Using the matrix elements in Table 3 and the phase space integrals $F_{j\pm}$ calculated in [3], we can deduce from the experimental data $\tau^{0\nu}_{1/2}(0^+ \to 2^+_1) > 8.2 \times 10^{23}$ yr (90% C.L.) [14] for the ^{76}Ge decay the constraints on the right-handed current couplings and the effective neutrino mass listed in Table 4. As for the ^{100}Mo decay, the Osaka group has obtained the limit $\tau^{0\nu}_{1/2}(0^+ \to 2^+_1) > 1.4 \times 10^{22}$ yr (68% C.L.) [15] assuming $\langle\lambda\rangle \neq 0$. Because of the differences in the angular correlation as we see from Fig. 1, an analysis of the same raw experimental data might yield a half-life limit significantly different from the above value especially for the case $\langle\eta\rangle \neq 0$. However we assume here just the same half-life limit also for the cases $\langle\eta\rangle \neq 0$ and $\langle m_\nu\rangle \neq 0$ in order to compare the resulting constraints with those from the ^{76}Ge data.

The limits which can be deduced from the experimental bound $\tau^{0\nu}_{1/2}(0^+ \to 0^+) > 5.7 \times 10^{25}$ yr (90% C.L.) [16] on the $0^+ \to 0^+$ decay of ^{76}Ge using the nuclear matrix elements of [17] are $|\langle\lambda\rangle| < 3.8 \times 10^{-7}$, $|\langle\eta\rangle| < 2.2 \times 10^{-9}$ and $|\langle m_\nu\rangle| < 0.19$ eV. Comparing these limits with those of Table 4, we notice the considerable difference in the *absolute* sensitivities between the $0^+ \to 0^+$ and $0^+ \to 2^+$ decays, which reflects the smaller Q-value as well as the higher electron partial waves associated with the latter. However, it should be stressed here that the *relative* sensitivities to $\langle m_\nu\rangle$ and $\langle\eta\rangle$ are comparable in both cases. In other words, $\langle m_\nu\rangle = 1$ eV would give roughly the same decay rate as $\langle\eta\rangle = 10^{-8}$ in the $0^+ \to 2^+$ as well as in the $0^+ \to 0^+$ decays. At the same time it should also be noted that the $0^+ \to 2^+$ decay is relatively more sensitive to $\langle\lambda\rangle$.

In summary, we have calculated $0^+ \to 2^+$ $0\nu\beta\beta$ decay rates taking into account the recoil corrections to the nuclear currents. As a result, the expression for the decay probability becomes a quadratic form of not only the effective

coupling constants $\langle\lambda\rangle$ and $\langle\eta\rangle$ of the right-handed leptonic currents but also the effective neutrino mass $\langle m_\nu\rangle$ which would be totally absent without the inclusion of the recoil corrections. In other words, the recoil corrections give the *lowest* order contribution to the $0^+ \to 2^+$ $0\nu\beta\beta$ decay for the case where $\langle\lambda\rangle = \langle\eta\rangle = 0$ and $\langle m_\nu\rangle \neq 0$. Furthermore, by the numerical calculation of the relevant nuclear matrix elements, we have demonstrated that the *relative* sensitivities of $0^+ \to 2^+$ decays to $\langle m_\nu\rangle$ and $\langle\eta\rangle$ are comparable to those of $0^+ \to 0^+$ decays.

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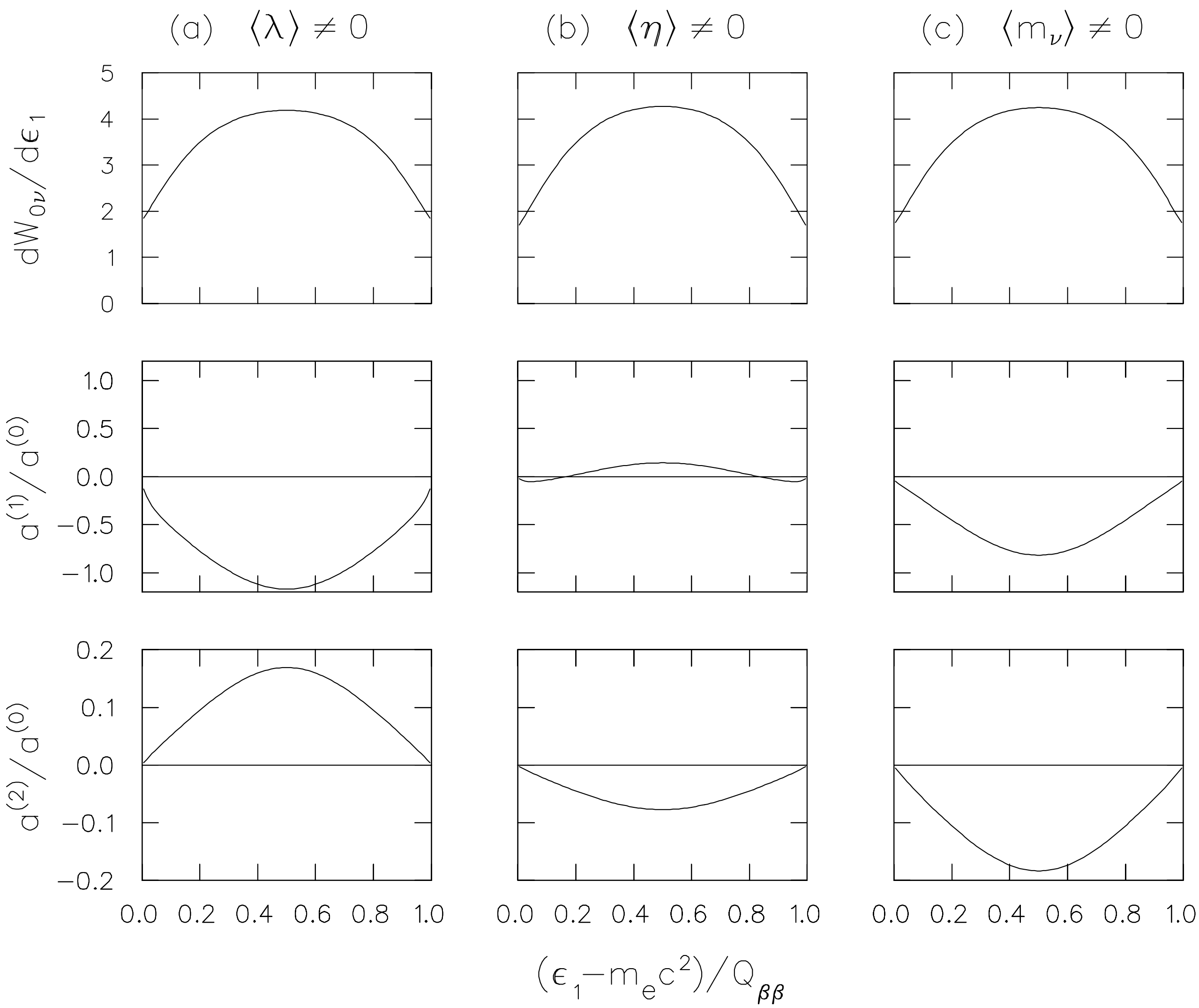

Fig. 1. Single electron spectrum $dW_{0\nu}/d\epsilon_1$ in arbitrary units and the ratios of the angular correlation coefficients $a^{(1)}/a^{(0)}$ and $a^{(2)}/a^{(0)}$ for the $0^+ \rightarrow 2_1^+$ $0\nu\beta\beta$ decay of ^{100}Mo. They are all plotted against the kinetic energy fraction of one of the two emitted electrons, where $Q_{\beta\beta}(0^+ \rightarrow 2_1^+) = 2.494$ MeV. Only one of the three lepton number violating parameters is assumed to be nonvanishing for each of the three cases: (a) $\langle\lambda\rangle \neq 0$, (b) $\langle\eta\rangle \neq 0$ and (c) $\langle m_\nu\rangle \neq 0$.

Table 1
The operators $\boldsymbol{M}_{inm}$ and the coefficients $C_{\mathrm{m}i}$, the latter in units of the electron-nucleon mass ratio m_e/M.

i	$\boldsymbol{M}_{inm}$	$C_{\mathrm{m}i}$
1	$-\sqrt{3}h'\boldsymbol{S}_0\boldsymbol{y}_2$	$-\frac{1}{3}[\mu_\beta(g_{\mathrm{V}}/g_{\mathrm{A}})+\frac{1}{2}]$
2	$h'\boldsymbol{S}_2$	$\frac{1}{6}[\mu_\beta(g_{\mathrm{V}}/g_{\mathrm{A}})-1]$
3	$h'[\boldsymbol{S}_2\otimes\boldsymbol{y}_2]^{(2)}$	$-\frac{\sqrt{7}}{4\sqrt{3}}[\mu_\beta(g_{\mathrm{V}}/g_{\mathrm{A}})-1]$
4	$h'\boldsymbol{y}_2$	$\frac{1}{2}(g_{\mathrm{V}}/g_{\mathrm{A}})^2$
5	$h'[\boldsymbol{S}_+\otimes\boldsymbol{y}_2]^{(2)}$	$\frac{\sqrt{3}}{4\sqrt{2}}[\mu_\beta(g_{\mathrm{V}}/g_{\mathrm{A}})^2-(g_{\mathrm{V}}/g_{\mathrm{A}})]$
14	$-\sqrt{3}h\boldsymbol{S}_0\boldsymbol{y}'_2$	$\frac{1}{3}$
15	$h\boldsymbol{y}'_2$	$-(g_{\mathrm{V}}/g_{\mathrm{A}})^2$
16	$H\boldsymbol{S}_2$	$-\frac{1}{2}[\mu_\beta(g_{\mathrm{V}}/g_{\mathrm{A}})-1]$
17	$h\boldsymbol{S}_2\boldsymbol{y}'_0$	$-\frac{1}{\sqrt{3}}$
18	$h[\boldsymbol{S}_2\otimes\boldsymbol{y}'_1]^{(2)}$	$-\frac{\sqrt{3}}{2}$
19	$h[\boldsymbol{S}_2\otimes\boldsymbol{y}'_2]^{(2)}$	$-\frac{\sqrt{7}}{2\sqrt{3}}$
20	$h[\boldsymbol{S}_+\otimes\boldsymbol{y}'_1]^{(2)}$	$\frac{1}{2\sqrt{2}}(g_{\mathrm{V}}/g_{\mathrm{A}})$
21	$h[\boldsymbol{S}_+\otimes\boldsymbol{y}'_2]^{(2)}$	$\frac{\sqrt{3}}{2\sqrt{2}}(g_{\mathrm{V}}/g_{\mathrm{A}})$
22	$h[\boldsymbol{S}_1\otimes\boldsymbol{Y}'_1]^{(2)}$	$-\frac{1}{4}$
23	$h[\boldsymbol{S}_1\otimes\boldsymbol{Y}'_2]^{(2)}$	$-\frac{\sqrt{3}}{4}$
24	$h[\boldsymbol{S}_-\otimes\boldsymbol{Y}'_1]^{(2)}$	$-\frac{1}{4\sqrt{2}}(g_{\mathrm{V}}/g_{\mathrm{A}})$
25	$h[\boldsymbol{S}_-\otimes\boldsymbol{Y}'_2]^{(2)}$	$-\frac{\sqrt{3}}{4\sqrt{2}}(g_{\mathrm{V}}/g_{\mathrm{A}})$

Table 2
Calculated matrix elements M_{m} for the ^{76}Ge and ^{100}Mo decays. The entries are the values of the products $C_{\mathrm{m}i}M_i$ and their sum M_{m} in units of $10^{-3}\mathrm{fm}^{-1}$.

i	^{76}Ge	^{100}Mo
1	−0.0229	−0.0077
2	0.0013	0.0003
3	0.0002	0.0008
4	−0.0017	−0.0011
5	−0.0003	0.0007
14	−0.0191	−0.0227
15	−0.0128	−0.0112
16	−0.0033	−0.0006
17	−0.0017	0.0000
18	−0.0028	0.0019
19	−0.0005	0.0001
20	0.0006	0.0005
21	0.0002	−0.0001
22	0.0020	−0.0000
23	0.0020	−0.0026
24	−0.0047	−0.0001
25	0.0012	−0.0010
sum	−0.0624	−0.0427

Table 3
Calculated matrix elements for the $0^+ \to 2_1^+$ $0\nu\beta\beta$ decays of ^{76}Ge and ^{100}Mo in units of $10^{-3}\mathrm{fm}^{-1}$.

	M_λ	M_η	M'_η	M_{m}
^{76}Ge	1.81 [a]	13.37 [a]	0.18 [a]	−0.0624
^{100}Mo	−6.33	3.38	5.17	−0.0427

[a] Ref. [11].

Table 4
Constraints on the right-handed current couplings and the effective neutrino mass.

	^{76}Ge	^{100}Mo
$\lvert\langle\lambda\rangle\rvert$	$< 8.9 \times 10^{-4}$	$< 3.9 \times 10^{-4}$
$\lvert\langle\eta\rangle\rvert$	$< 1.2 \times 10^{-4}$	$< 4.3 \times 10^{-4}$ [a]
$\lvert\langle m_\nu\rangle\rvert$ [eV]	$< 1.0 \times 10^{4}$	$< 2.2 \times 10^{4}$ [a]

[a] Assuming the same limit on $\tau_{1/2}^{0\nu}$ as the $\langle\lambda\rangle$ mode.